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Abstract: *We outline a view of how road networks interact with stream networks at the landscape scale and, based on examples from recent and current research, illustrate how these interactions might affect biological and ecological processes in stream and riparian systems. At the landscape scale, certain definable geometric interactions involving peak flows (floods) and debris flows (rapid movements of soil, sediment, and large wood down steep stream channels) are influenced by the arrangement of the road network relative to the stream network. Although disturbance patches are created by peak-flow and debris-flow disturbances in mountain landscapes without roads, roads can alter the landscape distributions of the starting and stopping points of debris flows, and they can alter the balance between the intensity of flood peaks and the stream network's resistance to change. We examined this conceptual model of interactions between road networks and stream networks based on observations from a number of studies in the H. J. Andrews Experimental Forest, Oregon (U.S.A.). Road networks appear to affect floods and debris flows and thus modify disturbance patch dynamics in stream and riparian networks in mountain landscapes. We speculate that these changes may influence the rates and patterns of survival and recovery of disturbed patches in stream networks, affecting ecosystem resilience, and we outline an approach for detecting such effects based on a patch dynamics perspective. A field sampling scheme for detecting the magnitude of various road effects on stream and riparian ecology could involve (1) landscape stratification of inherent stream network susceptibility to floods or debris flows, (2) overlay of road and stream networks and creation of areas with various densities of road-stream crossings, emphasizing midslope road-stream crossings, and (3) designations of expected high- and low-impact stream segments based on numbers of upstream road-stream crossings where sampling of selected biological variables would be conducted.*

Efectos de Carreteras en la Hidrología, Geomorfología y Parches de Perturbación en Redes de Arroyos

Resumen: *Desglozamos una perspectiva sobre la interacción entre redes carreteras y redes de arroyos a escala de paisaje e ilustramos como estas interacciones pueden afectar procesos biológicos y ecológicos en sistemas de arroyos y riparios en base a ejemplos que parten de investigaciones recientes y en proceso. A escala de paisaje, ciertas interacciones geométricas definibles y que involucran flujos-pico (inundaciones) y flujos de detritus (movimientos rápidos de suelo, sedimentos y piezas grandes de madera en canales con pendiente pronunciada) son influenciadas por los arreglos de la red de carreteras en relación con la red de arroyos. A pesar de que los parches de perturbación son creados por perturbaciones en los flujos-pico y en los flujos de detritus en paisajes montañosos sin carreteras, las carreteras pueden alterar las distribuciones de puntos de inicio y final de flujos de detritus en el paisaje y pueden alterar el balance entre la intensidad de los picos de inundación y la resistencia del arroyo al cambio. Examinamos este modelo conceptual de interacciones entre la red de arroyos y la red de carreteras en base a observaciones de una cantidad de estudios del Bosque Experimental Andrews, en Oregon. Las redes de carreteras aparentemente afectan las inundaciones y los flujos de detritus, esto modifica la dinámica de los parches de perturbación en redes de arroyos y zonas riparias de paisajes montañosos. Especulamos que estos cambios pueden influenciar las tasaa y patrones de*

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supervivencia y recuperación de parches perturbados en redes de arroyos, afectando la resistencia del ecosistema y detallamos una aproximación para detectar estos efectos en base a una perspectiva de dinámica de parches. Un esquema de muestre de campo para detectar la magnitud de varios efectos de las carreteras en la ecología de arroyos y zonas riparias podría involucrar (1) la estratificación de la susceptibilidad inherente de la red de arroyos a inundaciones o flujo de detritus en el paisaje, (2) la sobreposición de redes de arroyos y carreteras y la creación de cruces a mitad de la pendientes, y (3) la designación de segmentos esperados de bajo y alto impacto donde se realicen muestreos de variables biológicas selectas en base a números de cruces entre arroyos y carreteras que se encuentren arroyo arriba.

Introduction

Road networks have a great variety of effects on watersheds. Most existing studies of road effects on ecosystems are fine in scale and focus on terrestrial ecosystems (Forman & Alexander 1998). Landscape-scale studies of roads have emphasized "zones of influence" of roads extending laterally into terrestrial ecosystems (e.g., Forman & Deblinger, 2000). We offer a complementary approach that considers the effects of road networks on stream and riparian networks. This perspective is based on experience in steep mountain watersheds with high precipitation, forest cover, and road networks constructed for forestry land use, but the principles may apply to other ecosystems.

Early work in geomorphology (Horton 1945; Leopold et al. 1964) laid the groundwork for studies of network structure and associated hydrologic and geomorphic processes, and recent studies (e.g., Montgomery & Dietrich 1988, 1992) explain aspects of complex natural stream channel networks from elementary physical principles. Geomorphology studies in mountain stream networks, especially along the Pacific coast of the United States, emphasize a spatially and temporally explicit view of geomorphic processes, exploiting the availability of digital elevation data and capabilities of geographic information systems to examine landforms, streams, and geomorphic processes.

Stream networks collect episodic inputs of sediment and wood, provided by landslides and other processes, and transport this material episodically through a channel network (Jacobson 1995; Benda & Dunne 1997*a*, 1997*b*). Over time, especially during floods, the physical features of the stream—channels, bars, and floodplains—are created and modified by interactions among sediment, water, and wood (Lyons & Beschta 1983; Grant 1986; Wondzell & Swanson 1999). Thus the patch dynamics of stream networks and riparian forests reflect the history of hydrologic and geomorphic processes (Swanson et al. 1997; Benda et al. 1998).

Two key processes—floods (peak flows) and debris flows—have major influences on riparian vegetation patch dynamics in mountain landscapes, but they produce somewhat different spatial patterns of disturbance in stream and riparian networks. A peak streamflow event is triggered by a pulse of water input from precipitation and/or snowmelt routed through hillslopes and channels to produce a flood wave. Because flood waves are temporally continuous phenomena, peak flow events must be defined arbitrarily from the hydrograph, but the magnitude of each peak (its maximum height) can be determined precisely by field observations or stream gaging. Also, peak flows propagate downstream great distances and have longitudinally extensive zones of impact. Typically, a flood wave creates visibly disturbed patches in the stream network only where its damaging force exceeds local resistance to change; this balance between flood wave force and local resistance is influenced by several factors. Narrow bedrock zones or areas where the stream has been "hardened" (e.g., by roadfill) are less susceptible to disturbance, whereas stream segments below bends or in widened reaches have deposits of relatively fine sediment and colonizing vegetation that are less resistant to modification by the stream's energy (Grant & Swanson 1995).

Debris flows are rapid movements of soil, sediment, and organic matter (large wood) down steep stream channels. Debris flows most commonly originate from debris slides, which are rapid movements (velocities of approximately 10 m per second) of soil, sediment, and associated vegetation down hillslopes. In contrast to peak flows, debris flows produce discrete tracks of channel and riparian disturbance whose number and density per unit area can be precisely estimated, but the volumes of sediment moved may be difficult to measure because (among other difficulties) they may be removed by streamflow. Debris flow tracks can be mapped because they have distinct starting points, a relatively clearly defined zone of primary impact, and an identifiable stopping point. Individual tracks may reach tens of meters in width and several kilometers in length (Swanson et al. 1998; Snyder 2000; Nakamura et al. 2000). The location and proximal cause of individual debris flows also can be interpreted in the field, so they lend themselves to analyses of numbers, locations, and the types of patches created in a stream network.

Flood peaks and debris flows are hydrologic and geomorphic processes with landscape-scale expressions in the stream network that create aquatic and riparian patch dynamics critical to stream ecosystems (Pringle et al. 1988). The creation, destruction, and modification of stream geomorphic features such as channels, bars, and floodplains are tightly coupled with biotic features including riparian vegetation and lotic and benthic communities (Pringle et al. 1988; Swanson et al. 1988; Gregory et al. 1991). Stream organisms such as salmonids may be tied to the historical disturbance pattern over evolutionary time (Reeves et al. 1995), over multiple generations of spawning at a given site (Geist & Dauble 1998), or even at the scale of an individual spawning salmon (Montgomery et al. 1996). Infrequent, intense flooding is believed to produce larger, more severely disturbed stream and riparian patches than frequent, less intense flooding (Gregory et al. 1991; Michener & Haeuber 1998; Swanson et al. 1998). A reduction in severe, infrequent floods (e.g., by reservoir operations) reduces off-stream habitat for endangered fishes, whereas experimental floods increase it (Schmidt et al. 1998; Pitlick & Van Steeter 1998; Van Steeter & Pitlick 1998). In other words, native stream organisms appear to be linked integrally to the natural disturbance regime (sensu Reeves et al. 1995; Swanson et al. 1997) and the natural streamflow regime (sensu Poff et al. 1997).

Road networks constructed for forest harvest in the Pacific Northwest appear to have increased the magnitude and frequency of peak flows, debris slides, and debris flows relative to those in areas that are fully forested and fire-disturbed. Road construction is associated with increased frequency of landslides and other forms of erosion in steep forest landscapes (Swanson & Dyrness 1975; Nolan et al. 1995). A variety of mass movement and fluvial processes have been noted along road networks after intense flooding in this landscape (Wemple 1998). Increases in peak discharges have been significantly associated with forest harvest and road construction in both small experimental basins (<1 km^2) and in large basins (60–600 km^2) over the past 4–6 decades (Jones & Grant 1996; Thomas & Megahan 1998). The causes of increased peak discharges are controversial, but one of several possible mechanisms is that roads have changed the routing of water from hillslopes to streams (Montgomery 1994; Wemple et al. 1996).

We hypothesize that road network effects on flood peaks and debris flows modify patch dynamics in stream and riparian networks. Herein, we outline how road networks interact with stream networks at the landscape scale and, based on examples from recent and current research, illustrate how these interactions might affect biological and ecological processes in stream and riparian systems. Our approach produced a distinctly different picture of the spatial distribution of ecological responses to road networks than that of the road zone-of-influence approach used for assessing effects on terrestrial ecosystems. We sought to present a conceptual framework that is relevant for ecologists and conservation biologists in the process of assessing current ecosystem conditions and planning landscape-scale restoration activities. We hope that this framework will encourage scientists from many disciplines to work toward spatially explicit studies of road effects on whole stream networks.

Conceptual Model of Interactions between Road and Stream Networks

Our conceptual model is a series of premises. Landscapes contain patchwork and network structures defined by vegetation, soil, and other properties reflecting landform evolution, natural disturbances, and land management (Swanson et al. 1997). Patches consist of vegetation of various types or histories of disturbance by natural or management processes. We focused on two types of networks: natural physical networks, including streams, riparian zones, and ridges, and artificial networks, or roads (Fig. 1).

Flows of matter (water, mass movements, sediment, organisms) and energy follow gravitational flowpaths down hillslopes to channels and along channels in the stream network. Although other materials and transport processes (e.g., movement of suspended load, bedload, and coarse woody debris) might be considered, we focused on flood peaks and debris flows because they are best known and they illustrate many of the principles of interactions between road and stream networks in a landscape.

The stream drainage network is ordered: flows from smaller segments coalesce in successively larger segments. The road network consists of segments and junc-

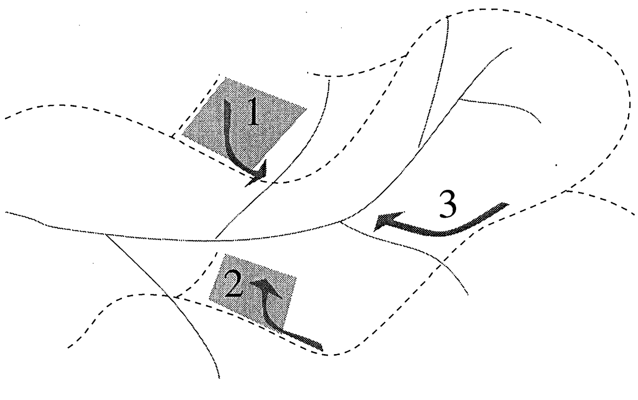

Figure 1. Three types of interactions may occur in a landscape among patches (gray polygons), a road network (dashed line), and a stream network (solid line): (1) patch to road, (2) road to patch, and (3) road to stream. In steep, forested mountain landscapes, patches may be stands of younger vegetation created by a natural disturbance such as wildfire or windthrow or by a human disturbance such as forest harvest.

tions and may be ordered in the sense that spur or dead-end roads sprout from trunk roads; usage intensity is highest and most constant along trunks and lowest and more episodic along spurs (Fig. 1). Some processes are affected by traffic levels (e.g., production of fine sediment, Reid & Dunne 1984), whereas others may not be affected by traffic (e.g., mass movements).

Stream and road networks are similar in five respects: they occupy a small portion of the landscape (commonly only a small percentage of total area), they are widely distributed, and they are "designed" to transport material and energy across a landscape. Stream and road networks also have a high edge length per unit area, hence, opportunity for interaction with neighboring patches. Also, streams and roads commonly occurs at similar densities in mesic or wet-climate mountain landscapes where logging has occurred (Wemple et al. 1996). Road and stream networks differ in that streams flow downslope, whereas roads cross steep slopes (Fig. 2), and roads themselves are not channels, although they often include a ditch that may function as a channel.

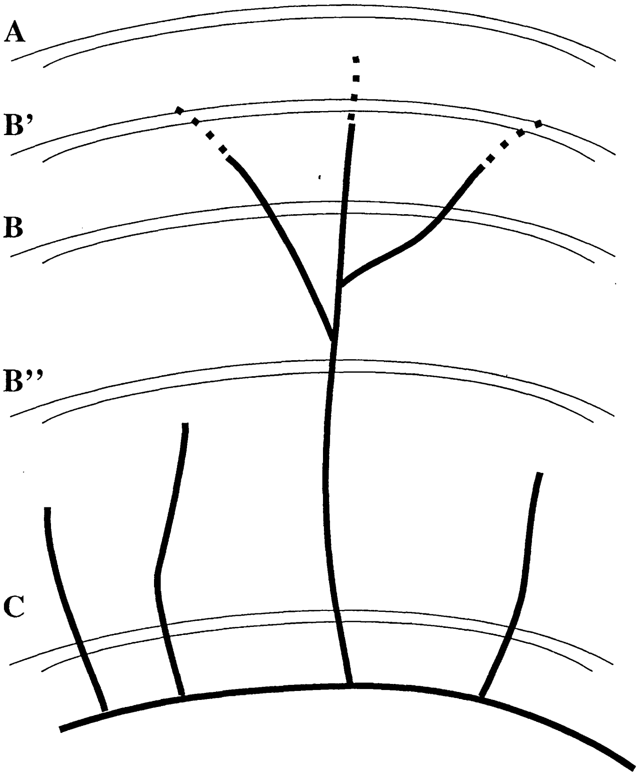

Figure 2. Effects of hillslope position and road design features on road-stream interactions. Roads (double lines) often cross steep tributary streams (dark solid lines) or ephemeral streams (dashed lines) at perpendicular angles in middle and lower hillslope positions (B', B, B"), thus directly affecting peak flows and debris flows. Valley floor roads often run parallel to mainstem streams (C), thus affecting lateral movement of the stream channel and its connectivity to the riparian zone.

Road location in the landscape, specifically hillslope position, strongly influences the type and frequency of interactions between roads and streams (Fig. 2). Roads near ridges have little direct interaction with streams (Montgomery 1994), but roads often cross small tributary streams at perpendicular angles in midslopes and lower slopes, and they commonly are parallel to main stream segments along valley floors (Fig. 2). Consequently, road-stream crossings may be concentrated in middle and lower hillslope positions.

This arrangement of roads relative to stream networks and gravitational flowpaths sets up certain definable geometric interactions involving flows of water and sediment. Energy, organisms, and material may move between patches and network segments or between road segments and stream segments (Fig. 1). Many types of interactions can occur (Fig. 3). A given road segment may act as a barrier, a net source, a net sink, or a corridor relative to flows of water and/or sediment.

Complex combinations of interactions can occur between road segments and flows of water (Fig. 4) or sediment (Fig. 5). Roads may act as corridors for flows of water on road surfaces (A and B, Fig. 4) or in roadside ditches (C, Fig. 4) and as sources of water to stream networks through culverts (D, Fig. 4) or gullies (E, Fig. 4) (Wemple et al. 1996). Roads also may act as sinks for sediment, intercepting slides (A, Fig. 5), as sources of slides (B, Fig. 5), or as corridors transmitting debris flows in stream channels (C, Fig. 5) (Wemple 1998). Encounters with roads may modify the magnitude and direction of flows of water and debris flows, and water flows may transform into debris flows or vice-versa.

The number or density of road-stream crossings provide a useful point of departure for evaluating interactions between road and stream networks at a landscape scale. Because stream and road drainage densities define the number of road-stream crossings (Fig. 6), they define a framework to examine how road design and topographic relief affect road influences on debris flows,

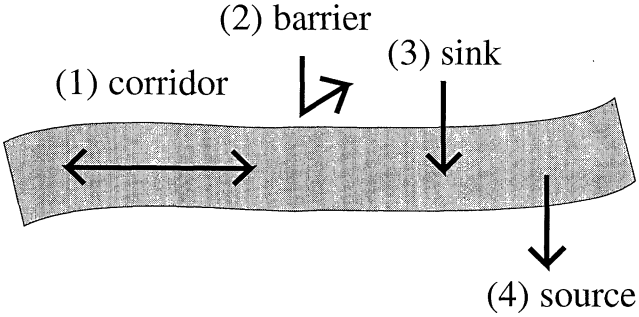

Figure 3. Four basic types of flow interactions with a road segment (shaded).

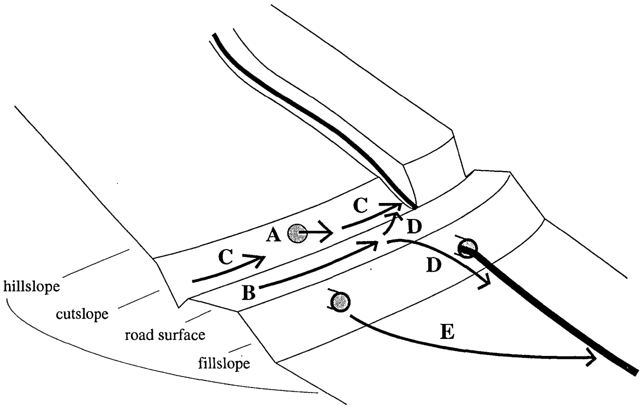

Figure 4. Five types of interactions involving water between a midslope road parallel to contour and a stream (heavy solid line): (A) subsurface flow interception, (B) surface flow on roads, (C) flow routing along ditches to streams, (D) flow along road surface to streams, and (E) flow in gullies to streams.

peak flows, and other measures of the stream network's response to roads.

Roads alter the balance between the intensity of peak flows and the stream and riparian network's resistance to change, whereas they alter the landscape distributions of the starting and stopping points of debris flows. Hence, the two processes may produce somewhat distinct patterns of affected stream network lengths. Systemic, high-severity hydrologic processes such as extreme flood peaks produce a set of disturbance patches controlled by site-specific patterns of resistance to change within the stream network. Road network interactions intensify and redistribute flood energy, thereby producing additional disturbance patches. This pattern of patches represents the stream segments downstream of high densities of road-stream crossings where flood energy may disturb the riparian zone (Fig. 7); the actual pattern of flood disturbance patches also will be controlled by factors such as valley floor width, the age and type of vegetation, and the amount of wood and sediment.

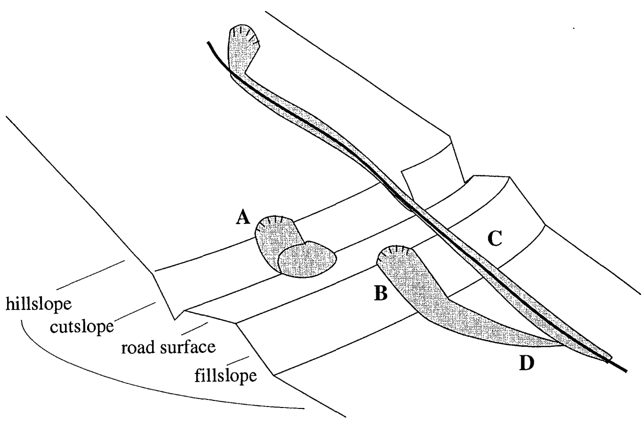

Figure 5. Types of interactions involving debris flows between a midslope road parallel to contour and a stream (heavy solid line): (A) cutslope slides, (B) fillslope slides, (C) debris flows that pass roads, and (D) fillslope slides that become debris flows.

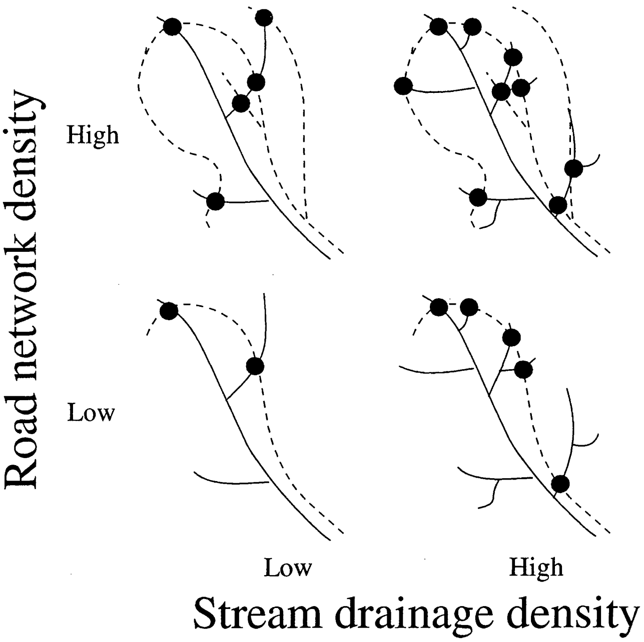

Figure 6. Effects of increasing drainage densities of the road network (dashed line) and the stream network (solid line) on the number of road-stream crossings (black dots) in a landscape.

On the other hand, localized, high-severity geomorphic processes such as debris flows produce a set of disturbance patches of discrete length extending from initiation sites that may be unaffected by roads. Road network interactions produce additional patches downstream from road-stream crossings where debris flows commonly are initiated (e.g., Swanson et al. 1998; Fig. 8). This pattern of scattered linear patches represents the stream segments where natural debris flows and those associated with roads expend large amounts of energy, scouring the stream bed and removing riparian vegetation, sediment, and wood. Many debris flow tracks end in piles of large wood and boulders deposited by the debris flow; in some cases, roads can stop debris flows, shortening their tracks.

Evidence from Andrews Forest, Oregon

We examined our conceptual model of interactions between road and stream networks based on a number of studies in the H. J. Andrews Experimental Forest, Oregon. The Andrews Forest, located on the western slope

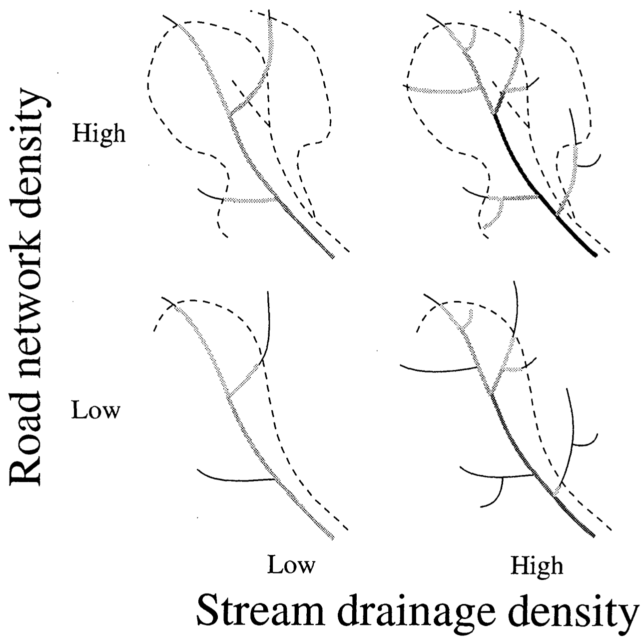

Figure 7. Spatial pattern of peak-flow disturbance patches (greater effect in darker shaded tones) created in a stream network below crossings of the road network (dashed lines) and stream network (solid or gray lines). Higher road and stream drainage densities increase the stream network length with high potential for road-related disturbances. The diagram illustrates a situation in which all road-stream crossings have equal and additive influences on peak flows and all stream segments respond equally. In a real landscape, the actual spatial pattern of stream network susceptibility to road effects on peak flows would be more patchy.

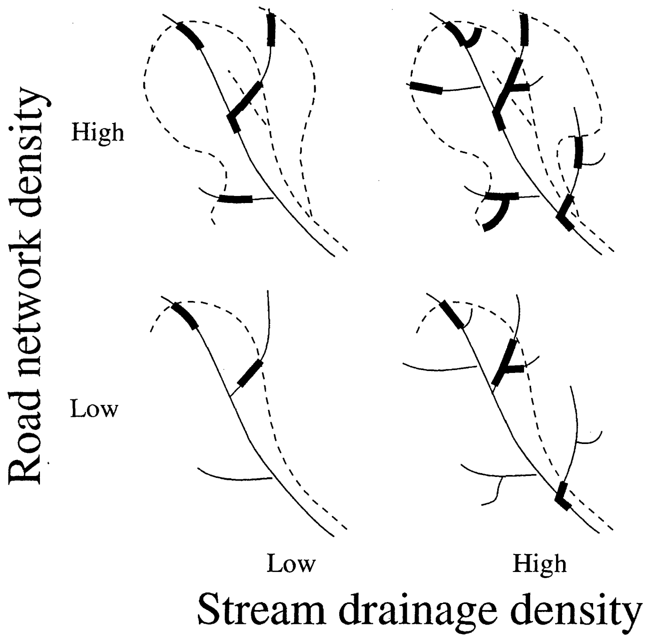

Figure 8. Spatial pattern of debris flow disturbance patches (heavy solid lines) created in a stream network below crossings of the road network (dashed lines) and stream network (thin solid lines). Higher road and stream drainage densities produce larger affected percentages of the stream network. The zones of primary disturbance by debris flows are emphasized, but areas downstream of these patches also may be disturbed. The effect of road-stream crossings in real landscapes is overstated because not every road-stream crossing generates debris flows. Debris flows also occur in the absence of roads, creating additional patches not shown here.

of the Cascade Range in Oregon, has a 50-year history of research on biophysical processes (McKee 1998). The Andrews Forest comprises one drainage basin with steep slopes on highly weathered volcanic substrates. Vegetation cover is mostly old-growth Douglas-fir (*Pseudotsuga menziesii*) forest. Twenty-five percent of the landscape has been harvested and converted to Douglas-fir plantations since 1950. The basin has a relatively high density of forest roads (approximately 2 km/km^2), most of which were constructed in the 1950s and 1960s (Wemple et al. 1996). We examined studies on peak flows and debris flows, evaluating the major forms of evidence of interactions between road and stream networks, the nature of the mechanisms involving roads, and the direction, magnitude, timing and locations of effects on stream channels.

Peak Flows

Three forms of evidence support the assertion that the road network is significantly hydrologically connected to the stream network in the Andrews Forest. First, in small experimental basins, partial logging (25% of basins) with roads appears to have increased large flood peaks (those that occur annually or less often) to the same or greater extent and for longer periods than 100% forest harvest (Jones & Grant 1996; Thomas & Megahan 1998; J. A. Jones, unpublished data). This implies that roads can affect the manner in which incoming precipitation is routed through a basin to produce a flood (Jones & Grant 1996). Second, surveys of road drainage systems indicate that significant portions of the road network have the potential to act as extensions of the stream drainage network (Wemple et al. 1996). Third, Wemple (1998) quantified the amounts of water carried by road segments and showed that this water could be delivered to the stream network to coincide with the flood peak.

Two mechanisms involving peak flows produce interactions between road and stream networks. The cutbanks of roads collect water flowing slowly down a hillslope below the soil surface. Some segments of the drainage ditches alongside the roads carry water rapidly and directly to streams or to culverts that concentrate water flow and carve gullies down hillslopes to streams (Wemple et al. 1996; Wemple 1998). Interactions between road and stream networks involving water flow seem to have the potential to synchronize water flow through the basin during a storm event, thus increasing the height of the flood peak (Jones & Grant 1996).

The magnitude of increase in flood peaks attributable to interactions between road and stream networks is difficult to separate from the coincident effects of forest harvest. In small harvested basins in western Oregon where road densities are 1-3 km/km^2, roads may increase the height of the peak by at most a few tens of percentage points for floods occurring annually or less frequently (Jones & Grant 1996; Thomas & Megahan 1998; J. A. Jones, unpublished data). In large basins where forest harvest also is confounded with road construction, the combined effects of forest harvest (<25% of basin areas) and road construction appear to have increased floods that occur annually or less frequently by, at most, 100% over the past 50 years (Jones & Grant 1996; Thomas & Megahan 1998). This increase is small relative to the interannual fluctuations in flood size, but it may represent a shift in the distribution of all floods to higher levels than before road construction and harvest occurred.

Debris Flows

The primary evidence of road and stream network effects on debris flows in the Andrews Forest area is the spatial pattern of debris flow tracks from inventory of 50 years of debris flows and debris slides (Swanson & Dyrness 1975; Snyder 2000; Nakamura et al. 2000). Field observations indicate that debris flows frequently are initiated or augmented by debris slides associated with roads; one out of three first- through third-order stream channels crossed by a road at the midslope position were associated with debris-flow initiation (Snyder 2000).

Two mechanisms involving debris flows produce interactions between road and stream networks. Many forest roads in the Andrews were constructed by excavating part of the hillslope and using this material to support the downhill side of the road ("cut-and-fill" roads). During heavy rain events, many small landslides originate from the downslope side of such road segments (the "fillslope"). When these slides occur close to streams, they often reach the streams and become debris flows (Swanson & Dyrness 1975; Wemple 1998; Nakamura et al. 2000). During heavy rains, debris flows also may be triggered by small landslides from forested hillslopes. A second form of road-stream interaction occurs when one of these debris flows moves down a stream channel, encounters a road, and either carries the road fill material further down the stream or stops on the road (Wemple 1998; Swanson et al., unpublished data).

The major effect of roads on streams produced by debris flows is severe disturbance of the stream channel, including removal or rearrangement of all material in some stream segments and deposits of sediment and wood in others. Debris flow tracks were 14 times more frequent per unit area of road than of undisturbed forest in the Andrews Forest and neighboring Blue River basins (Snyder 2000). Debris flow disturbances to streams occur mainly during extreme floods. The most severe effects occur in small, steep stream segments, but some sediment also may be transported to stream segments downstream of these highly disturbed areas, creating additional though less severe disturbances (Snyder 2000; Johnson et al. 2000; Nakamura et al. 2000.

Biological Implications for Stream Networks

Stream networks in both unroaded and roaded landscapes experience both patchy and pervasive disturbances. A key biological implication of floods and debris flows is that they affect only a few percentage of the total area (Miles & Swanson 1986) but tens of percentage of the stream network (Snyder 2000) in mountainous landscapes. Although roads can increase the frequency and extent of these types of disturbances, several factors make it difficult to isolate the extent of road influence on stream and riparian patch dynamics. Disturbance associated with major floods is extremely varied in severity and intensity in complex stream and riparian systems, even when the overall flood disturbance seems pervasive (Swanson et al. 1998; Johnson et al. 2000; Nakamura et al. 2000). Many studies of hydrologic, geomorphic, and ecological processes in stream networks have been conducted in roaded basins, and few studies have been conducted in large areas without roads. No studies we know of have related riparian or benthic habitat patch dynamics and ecology directly to road network distributions. We outline an approach to such studies, emphasizing areas that need research.

A key ecological implication of hydrologic and geomorphic disturbance patterns is that undisturbed areas may function as refuges from disturbance and sources of colonists in the post-disturbance recovery period (Sedell et al. 1990). The patchy character of flood flow and debris flow disturbances (Johnson et al. 2000; Nakamura et al. 2000) leaves numerous refuges in headwater channels undisturbed by debris flows and in undisturbed portions of mainstem channels. Thus, the network structure of stream and riparian systems contributes to their resilience to flood disturbance, and dispersal from undisturbed sites can help speed recovery in disturbed zones. If roads increase the frequency and intensity of flood peaks and debris flows, this may increase the extent of debris flows in small streams and possibly the extent of riparian-zone disturbance along main channels, and it may reduce the extent of refuges. Hence, road-network effects on the spatial pattern of disturbance may influence the rates of survival and recovery of disturbed patches in stream networks, which affects ecosystem resilience.

Observed debris-flow tracks typically disturb stream and riparian areas in only a few tributaries in the upper parts of stream networks (Nakamura et al. 2000) (Figs. 3 & 4). Because many tributaries within basins affected by debris flow do not experience such severe disturbance, they serve as refuges during floods. For example, Hunter (1998) observed low densities of amphibians in debris flow tracks created in the previous winter's flood, but amphibian populations in channels that had not experienced debris flows changed little after the flood.

Extreme flood peaks also typically disturb only some portions of the stream network. Flowing water alone is unlikely to damage riparian vegetation, but when a flood carries floating woody debris, especially batches of "congested wood" (Braudrick et al. 2000), vegetation is likely to be toppled or removed (Johnson et al. 2000). Long, narrow patches of disturbed vegetation and undisturbed habitat are common in unconstrained stream segments (e.g., in wide valley floors). These undisturbed patches provide refuges from flood disturbance arrayed both laterally away from the main channel and longitudinally along the channel (Swanson et al. 1998; Fig. 5).

Although we have separated peak flows from debris flows in this discussion, they are confounded. Flood peaks may initiate debris flows, and they may magnify, redistribute, or mute the disturbances produced by debris flows. Debris flows from tributary channels may enter main channels and interact with flood flows, providing batches of woody debris that serve as tools to produce patches of riparian disturbance (Wondzell & Swanson 1999; Johnson et al. 2000; Nakamura et al. 2000.

Biological responses to a disturbance event may be affected by the hillslope position of road-stream interactions. In the Andrews Forest and vicinity, roads in middle hillslope positions were net sources of sediment to the stream network, whereas valley floor roads were net sinks, and the frequency of erosion and deposition features associated with roads was an order of magnitude higher in valley floors than near ridges (Wemple 1998). Stream segments below midslope roads were more likely to be disturbed by debris flows than similar segments without roads (Snyder 2000). Less disturbance may occur in stream segments downstream of valley floor roads than those downstream from midslope roads (Wemple 1998). Roads constructed on valley floors, however, may limit organisms' access to floodplain and secondary channel areas that might otherwise serve as refuges and may limit dispersal of organisms to recolonize flood-disturbed areas.

Assessing Effects of Roads on Stream Networks

Our observations, hypotheses, and perspectives on interactions of road and stream networks, based on field studies conducted in the Pacific Northwest, have several implications for evaluating roads in the context of research, management, and conservation studies. Basins such as Lookout Creek in the Andrews Forest are heterogeneous; they contain areas of naturally high and low rates of peak flow and debris flow production that may affect distributions of habitat and organisms in time and space. Against this backdrop of natural processes and patterns, we propose that the effects of roads on peak flows and debris flows will be greatest downstream of individual road-stream crossings and downstream of areas of high densities of such crossings. Therefore, a field sampling scheme for detecting the magnitude of various road effects on stream and riparian ecology could involve (1) landscape stratification of inherent stream network susceptibility to floods or debris flows, (2) overlay of road and stream networks and creation of areas with various densities of road-stream crossings, emphasizing midslope road-stream crossings, and (3) designations of expected high- and low-impact stream segments based on numbers of upstream road-stream crossings where sampling of selected biological variables would be conducted. It is critical that such locations be selected and interpreted based on their positions in the whole stream network in order to account for the effects of the spatial arrangement of disturbance patches and refugia.

Further Work

We have not attempted to prove that road-stream interactions involving peak flows and debris flows modify the ecology of stream networks, but rather to set out a framework for understanding how such interactions might occur. Field studies may help test how stream disturbances created by extreme floods are related to road-network effects on peak flows and debris flows.

Although we focused on two processes, peak flows and debris flows, other hydrologic and geomorphic processes are influenced by road-stream interactions. Sediment and wood transport is inherently tied to flood- and debris-flow processes and is modified by roads (Reid 1981; Reid & Dunne 1984; Megahan 1987; Bilby et al. 1989; Wemple 1998; Braudrick & Grant 2000; Braudrick et al. 2000; Johnson et al. 2000). Also, interconnected road and stream networks have other functions, notably an ability to facilitate flows along nongravitational pathways. For example, evidence presented in Parendes and Jones (this issue) indicates that propagules of exotic plants may be dispersed along forest roads and hence along the stream network from road-stream crossings. These multiple functions of roads have potentially widespread effects on stream networks and deserve further study.

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